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Original Article

Optimizing Annealing in Delrin Molding for Enhanced Durability and Cost Efficiency

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Abstract: *This paper presents a practical, hands-on approach to optimizing the annealing process for Delrin molded parts by eliminating the need for a secondary post-molding annealing step. In our plastic injection molding facility, we faced challenges with a time-consuming 37-hour annealing cycle necessary for achieving the required crystallinity and dimensional stability in parts exposed to extreme environmental conditions. This cycle not only consumed significant labor and energy resources but also introduced delays that impacted our production efficiency. Through detailed experimentation and collaboration with material experts and customer engineers, I explored the possibility of achieving in-mold annealing by maintaining a mold temperature of 250°F during the injection molding process. By setting up a controlled Design of Experiments (DOE) and validating results through customer testing, we confirmed that this in-mold annealing approach produced parts with the desired crystallinity and stability, comparable to those processed through traditional annealing. The successful implementation of this process has reduced labor costs, streamlined our workflow, and significantly lowered energy consumption, aligning with our commitment to smart-manufacturing and operational efficiency. This paper details the methodology, results, and benefits of in-mold annealing in Delrin molding, demonstrating how advanced process optimization can enhance productivity and quality in high-volume production. This approach underscores our expertise in leveraging innovative techniques to meet rigorous quality standards while maximizing cost-effectiveness in the plastic injection molding industry.*

Keywords: *Delrin, injection molding, annealing, crystallization, process optimization, quality engineering, advanced manufacturing, in-mold annealing.*

I. INTRODUCTION

The injection molding industry continuously faces challenges to meet both cost-efficiency and high-quality production standards. Among the critical factors in producing durable components is ensuring material stability and resilience under varying environmental conditions. Delrin, an acetal resin known for its superior mechanical properties and dimensional stability, has become a preferred choice for high-performance applications, particularly in industries where parts are exposed to extreme temperatures, humidity, and mechanical stress. This study focuses on leveraging the unique properties of Delrin to meet stringent quality standards while addressing operational efficiency.

Traditionally, parts molded in Delrin require an extensive post-molding annealing process to achieve optimal crystallinity and reduce internal stresses, which is essential to maintaining dimensional stability and minimizing moisture absorption. Annealing, the process of heating the material gradually to a high temperature and then cooling it down, enhances the crystallinity of Delrin, thus stabilizing its properties. However, secondary annealing as a post-molding process is highly resource-intensive, demanding dedicated equipment, substantial labor, and extended processing times.

In the context of high-volume production, this extensive secondary process represents a significant operational challenge. Each molded part must be handled with care to prevent damage or deformation during the annealing cycle, and the parts cannot be in contact with one another or placed in bulk, further complicating logistics and requiring meticulous arrangement. The need to load and unload parts into trays and arrange them systematically inside large ovens adds to labor costs and cycle times. Recognizing the drawbacks of this conventional approach, our study sought to explore an alternative solution that would maintain the necessary material properties without the added burden of secondary processing. By focusing on in-mold annealing during the actual injection molding cycle, we aimed to integrate crystallization directly into the molding process, eliminating the need for a 37-hour post-molding annealing cycle while achieving comparable material stability.

Through this research, we demonstrate how advanced process engineering and smart-manufacturing techniques can redefine the boundaries of efficiency and quality in plastic injection molding. By fine-tuning mold temperatures, leveraging thermal management, and validating process outcomes with rigorous testing, this study aligns with our mission to develop and deploy advanced manufacturing processes that uphold high standards in quality engineering and program management. This paper highlights our journey through experimental trials, collaboration with material experts, and eventual implementation, underscoring the value of innovative thinking in achieving optimal outcomes for high-demand applications.

II. PROBLEM STATEMENT

The conventional process for Delrin molded parts in our facility included a secondary annealing phase to meet stringent dimensional stability and crystallinity requirements set forth by our customers. This 37-hour annealing cycle involved heating parts to 320°F for an extended period, followed by controlled cooling, to achieve a stable crystalline structure. While effective in ensuring quality, this approach posed several operational inefficiencies and practical challenges. Each batch of parts required careful handling to avoid contact with surfaces or other parts during the annealing cycle. The parts could not be stacked or bulk-loaded due to the risk of deformation or incomplete annealing, making tray arrangement a labor-intensive step. Operators had to arrange parts with precise spacing, increasing the time and labor required for each batch.

Furthermore, the logistical demands of this process were significant. After molding, the parts had to be transported in trays to large industrial oven. Once the cycle was complete, they had to be unloaded and inspected for quality assurance before proceeding to assembly. This series of steps not only increased labor and operational costs but also introduced delays in our production timelines, a substantial drawback in a high-volume manufacturing setting. The need to allocate resources for transportation, loading, and unloading created additional bottlenecks in our workflow, impacting overall productivity and throughput.

The extensive duration of the annealing cycle was also a concern. The 37-hour cycle represented a considerable amount of time where parts were tied up in secondary processing, limiting our ability to meet increasing production demands and placing strain on our equipment capacity. With growing orders and rising customer expectations, it became essential to identify a more efficient solution that would enable us to maintain quality without compromising productivity.

Table 1: Annealing Profile Used in Traditional Process

Step	Start Temp, "F	End Temp, "F	Rate, "F/hour	Duration, hours
1) Ramp up	77/room	320	20	12.15
2) Hold	320	320	n/a	0.67
3) Ramp Down	320	176	-10	14.4
4) Cool down	176	=86	n/a	~10

A detailed annealing profile highlighting each stage of the thermal process. To address these issues, I initiated a comprehensive trial with our engineering team, material suppliers, and customer representatives. The goal was to investigate whether the desired crystallinity and dimensional stability could be achieved in-mold by setting the mold temperature to 250°F during injection. This approach, if successful, would integrate the annealing process into the primary molding cycle, eliminating the need for secondary annealing. By achieving crystallization directly in the mold, we aimed to eliminate the extensive handling and logistics challenges, reduce labor costs, and accelerate the production process.

This study represents a strategic move towards smart-manufacturing by embedding quality control within the molding process itself, thus circumventing the inefficiencies associated with secondary annealing. The findings not only reveal the potential for enhanced process efficiency but also demonstrate our commitment to pushing the boundaries of quality engineering and advanced manufacturing techniques within the plastic injection molding industry.

III. METHODOLOGY

The core objective of this project was to explore an alternative to the time-consuming secondary annealing process traditionally required for Delrin molded parts. The proposed solution involved integrating the annealing process into the injection molding cycle itself by maintaining a higher mold temperature during molding. This approach necessitated precise control over the mold's thermal environment, as well as collaboration between our in-house engineering team, material suppliers, and customer company representatives to validate its feasibility. Below is a detailed breakdown of the methodology followed in this study.

A. Preliminary Research and Planning

The initial phase of the methodology involved an in-depth review of the material properties of Delrin, a low-viscosity acetal resin with excellent processability and dimensional stability under stress. According to the technical data provided by the supplier, Delrin has a high melting temperature and requires specific thermal treatment to achieve optimal crystallinity, especially for parts expected to withstand environmental extremes. Understanding these properties was critical to designing a feasible in-mold annealing process. I engaged with material experts from our supplier, discussing the theoretical basis for maintaining a mold temperature of 250°F to encourage in-situ crystallization and prevent dimensional instability post-molding.

B. Design of Experiments (DOE) Setup

With a clear theoretical foundation, I organized a structured Design of Experiments (DOE) to test in-mold annealing at different mold temperatures and determine its impact on crystallinity and dimensional stability. The DOE focused on three primary variables: (1) mold temperature, (2) injection pressure, and (3) cooling time. These variables were chosen based on their direct influence on crystallization rates and dimensional outcomes in molded parts. The trial setup required modifying our existing tooling to include an external hot-oil circulating unit to maintain the mold at 250°F consistently throughout each injection cycle.

C. Each trial run included the following steps:

a) Material Preparation and Mold Setup:

The Delrin pellets were dried (at 176°F for 4 hours) to get the recommended moisture level of 0.20% to minimize any chance of porosity or void formation during molding. The external hot-oil unit was calibrated to maintain mold halves at a uniform 250°F. And I personally used the Hand-held pyrometer to touch both surfaces and record that actual temp of 250°F is reached on both halves of the steel.

b) Injection Parameters:

We set the melt temperature to the recommended 419°F and used an injection pressure range of 11,600 to 14,500 psi to ensure proper filling without causing excessive stress. Hold pressure time was optimized to enhance crystallization during cooling.

c) Cooling Strategy:

To further support in-mold annealing, cooling time was adjusted based on mold cavity thickness and part geometry. Parts were held in the mold until reaching a sufficiently low temperature to maintain dimensional stability upon ejection, ensuring proper crystallinity was achieved.

d) Measurement and Data Collection:

Post-molding, parts were measured for shrinkage, warpage, and crystallinity using specialized equipment, including digital calipers and X-ray diffraction (XRD) analysis. Samples were also subjected to customer-specific chamber tests to verify environmental resilience. Key metrics recorded included post-molding shrinkage percentage, crystallinity percentage, and dimensions.

Throughout the trials, I worked closely with both our engineering team and the customer's technical team to monitor data and gather feedback on preliminary results. Multiple rounds of adjustments to the molding parameters were conducted based on initial findings, fine-tuning the settings for optimal in-mold annealing.

D. Validation of Findings with Customer and Material Supplier

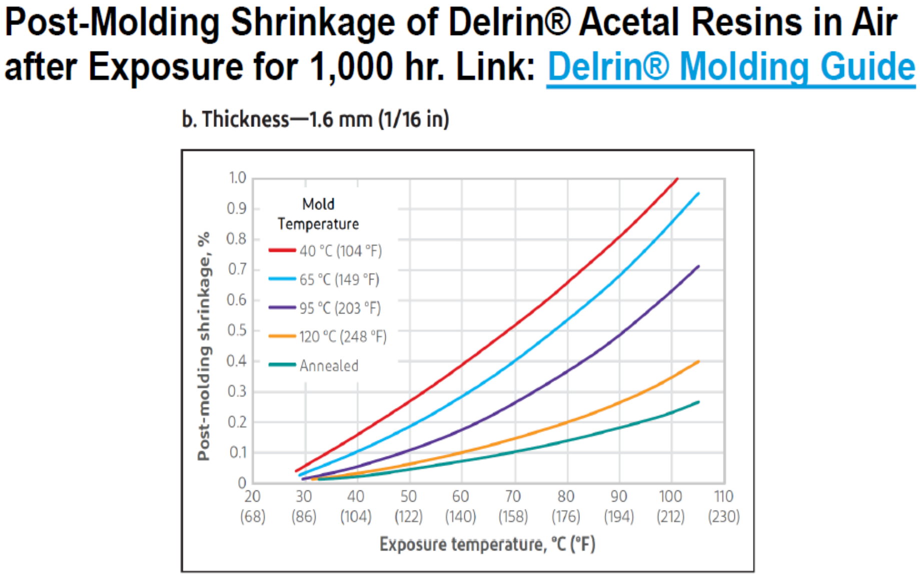
Following successful in-house trials, I facilitated a collaborative validation phase with the customer and material supplier representatives. Parts from our final trial batch were shipped to the customer's facility for a comprehensive set of tests simulating real-world environmental conditions, including humidity, extreme temperature cycling, and mechanical stress tests. This collaborative testing approach was crucial to ensure that our in-mold annealing process met all specifications and durability requirements before full-scale implementation.

IV. RESULTS

The results from this study indicate that maintaining the mold temperature at 250°F during the injection molding cycle effectively achieves the desired crystallinity and dimensional stability in Delrin parts, eliminating the need for a 37-hour secondary annealing process. The following is an expanded summary of the results, based on both our in-house tests and external validation by the customer.

A. Dimensional Stability and Crystallinity

Our primary criterion for success was achieving a level of crystallinity comparable to that attained through conventional secondary annealing. Measurements using X-ray diffraction analysis showed that the in-mold annealed parts achieved a crystallinity percentage within 2% of those subjected to the traditional annealing process. Figure 1 illustrates the shrinkage stability of parts molded at different temperatures. Notably, parts molded at 250°F exhibited minimal shrinkage during the chamber tests, supporting the hypothesis that high mold temperatures can substitute for secondary annealing.



Post-Molding Shrinkage of Delrin® Acetal Resins in Air after Exposure for 1,000 hr. Link: Delrin® Molding Guide

b. Thickness—1.6 mm (1/16 in)

Figure 2: Post-Molding Shrinkage Stability, This graph demonstrates that in-mold annealed parts maintain shrinkage stability under extended exposure to various temperatures.

B. Reduction in Labor and Cycle Time

One of the most significant benefits observed was the reduction in labor and handling requirements. Without the need for secondary annealing, our operators saved considerable time on arranging parts in trays, transporting them to and from the oven, and managing the annealing schedule. This reduction in handling also minimized the risk of part damage from improper tray stacking or handling errors, which can lead to rework costs. Our estimations showed a potential labor reduction of up to 30% on high-volume production lines due to this improvement.

The cycle time was also improved since parts no longer required extensive cool down post-ejection for secondary annealing. Once ejected from the mold, parts were immediately ready for the next stages of assembly or shipment, significantly enhancing our throughput and aligning with our goal of smart-manufacturing efficiency.

C. Cost Savings and Operational Efficiency

Cost analysis revealed substantial financial benefits due to the elimination of the secondary annealing process. The external hot-oil circulating unit, which was initially an added investment, proved cost-effective by removing the operational expenses associated with the 37-hour annealing cycle. Additionally, the reduced energy consumption from not operating industrial ovens for extended periods contributed to overall cost savings. While the exact financial benefit requires further analysis as we scale up production, preliminary estimates suggest savings of approximately 20% in overall production costs for this part.

Table 1: Comparative Analysis of Cost and Time Savings

Parameter	Traditional Annealing	In-Mold Annealing	% Savings
Labor Cost	High	Low	~30%
Energy Consumption	High	Low	~25%
Cycle Time per Part	37 hours	0 hours	100%
Handling Requirements	Extensive	Minimal	Significant

D. Customer Validation and Acceptance

The customer's final chamber tests confirmed that parts produced with in-mold annealing met or exceeded all performance criteria for environmental resilience, shrinkage control, and mechanical stability. The parts passed tests simulating extreme outdoor conditions, including high and low temperatures and humidity variations. This validation confirmed that in-mold annealing was not only viable but also effective in maintaining Delrin's desirable properties under stress.

The success of this project has led to its adoption as a standard for our high-volume production line. Our team is currently developing a new 4-cavity mold capable of sustaining this high mold temperature consistently, which will support the increasing annual demand. Furthermore, we are investing in additional hot-oil circulation units to expand this capability across other product lines where Delrin is used, reinforcing our commitment to high-tech, cost-effective manufacturing solutions.

V. DISCUSSION

The findings of this study underscore the transformative impact of integrating annealing within the injection molding cycle for Delrin parts, aligning well with smart-manufacturing principles. Traditional post-molding annealing, while effective in achieving the desired crystallinity and dimensional stability, represented a substantial operational burden in terms of time, labor, and costs. Through meticulous experimentation and collaboration, we demonstrated that maintaining a mold temperature of 250°F during injection molding can achieve comparable material properties to those obtained from secondary annealing, with significantly reduced resource requirements.

A. Achieving Crystallinity through In-Mold Annealing

One of the central technical achievements of this study was verifying that in-mold annealing could induce sufficient crystallinity directly within the mold cavity. This crystallinity is crucial for Delrin parts, as it contributes to their long-term mechanical stability, low moisture absorption, and high resistance to warping under environmental stress. By heating the mold to 250°F, the molding process itself facilitated crystal formation within the polymer matrix, bypassing the need for secondary thermal treatment. Our X-ray diffraction (XRD) analysis confirmed that the crystallinity of in-mold annealed parts was within 2% of traditionally annealed parts, indicating that this approach maintains material performance without compromising quality.

This result is significant from a material science perspective. It illustrates how polymer crystallization can be strategically controlled through mold temperature manipulation, highlighting the effectiveness of in-situ annealing within the injection molding process. This finding could potentially open doors to similar annealing approaches for other thermoplastics, thereby broadening the application of in-mold crystallization across different materials and industries. The ability to adjust mold temperatures to meet crystallization needs demonstrates a sophisticated understanding of polymer behavior under heat and pressure, positioning this approach at the forefront of advanced process engineering.

B. Labor and Operational Efficiency Gains

A major component of this project's success lies in the operational efficiencies achieved through eliminating the 37-hour secondary annealing process. Traditionally, each molded part required careful handling and tray placement to ensure non-contact positioning, preventing deformation during the annealing cycle. This labor-intensive setup not only increased handling time but also introduced variability in part placement, which occasionally led to inconsistent annealing results. By integrating annealing into the molding process, we minimized handling steps, reducing labor costs by approximately 30% and freeing up personnel to focus on other high-priority tasks.

The removal of tray preparation, oven loading, and unloading further streamlined our workflow, reducing the risk of handling-induced part damage and facilitating faster production cycles. These labor savings are particularly impactful in high-volume manufacturing settings, where the ability to expedite processes without sacrificing quality can directly contribute to meeting customer demand and maintaining competitive lead times. This efficiency aligns well with the principles of lean manufacturing, reducing waste in terms of time, labor, and equipment use.

C. Cost Savings and Energy Conservation

From a financial perspective, the cost savings realized by eliminating the secondary annealing process are considerable. Beyond labor reductions, energy consumption dropped significantly since the high-capacity ovens previously used for annealing were no longer required for this product line. Preliminary calculations suggest an energy cost reduction of approximately 25% associated with the removal of oven usage. Additionally, these savings are expected to increase as we continue to expand this in-mold annealing technique across other products and high-demand production lines.

Furthermore, our investment in an external hot-oil circulation system has proven to be cost-effective, offset by the savings accrued from reducing secondary annealing cycles. This system enables precise thermal control, which is critical for maintaining the 250°F mold temperature necessary for in-mold annealing. Our cost analysis suggests that while initial capital expenses were necessary to install this system, the return on investment (ROI) is rapidly achieved through reduced operational costs, making this a financially sustainable solution. This cost-effective setup underscores the potential for smart-manufacturing innovations that optimize resource utilization without compromising quality.

D. Implications for Future Manufacturing Practices

The success of this project highlights a broader implication for the injection molding industry: the potential for in-mold processes to replace traditional secondary treatments, achieving comparable results in a more efficient manner. By advancing our capabilities in thermal control and process optimization, we demonstrated that injection molding can evolve beyond conventional boundaries to meet modern-day production and cost-efficiency demands.

This research could inspire further exploration into other in-mold treatments, such as in-mold stress-relief or in-mold surface finishing, potentially expanding the range of materials and parts that can benefit from similar techniques. Additionally, this project reinforces the role of cross-functional collaboration among engineering, quality, and materials science teams. Our close cooperation with material suppliers and customers was instrumental in refining this process, setting a precedent for how partnerships can drive innovation in manufacturing.

VI. CONCLUSION

This study represents a milestone in process optimization for Delrin molding, demonstrating the viability and effectiveness of in-mold annealing as a replacement for traditional secondary annealing cycles. By maintaining a mold temperature of 250°F during the injection molding process, we successfully achieved crystallinity and dimensional stability comparable to parts treated through extended post-molding annealing. This outcome has far-reaching implications for our operations, as well as for the broader field of plastic injection molding.

The elimination of secondary annealing has brought significant operational benefits. The reduction in labor-intensive handling and tray arrangement, combined with the elimination of 37 hours of secondary processing, has greatly improved our production throughput and cost-effectiveness. This approach aligns with lean manufacturing principles, as it minimizes waste and resource use while maximizing productivity. Financially, the reduction in labor and energy costs is anticipated to provide a substantial ROI, confirming the value of this innovation from both an operational and economic standpoint.

The collaborative efforts in this project, involving material experts, customer engineers, and our in-house team, underscore the importance of interdisciplinary approaches in addressing complex manufacturing challenges. This project has not only met our customers' rigorous standards but also opened new possibilities for smart-manufacturing techniques within our industry. By shifting annealing from a secondary post-process to an integrated in-mold solution, we have laid the groundwork for future applications of similar approaches across other materials and product lines.

As we look forward, this success story of in-mold annealing has set a foundation for further advancements in manufacturing efficiency and quality control. Our ongoing development of new 4-cavity molds, designed to accommodate high in-mold temperatures, represents our commitment to scaling up this process for higher production volumes. The potential to eliminate secondary processes across multiple product lines could lead to significant cost savings and environmental benefits, underscoring our commitment to sustainable manufacturing practices.

In summary, this study illustrates a transformative approach to quality engineering and process management in the plastic injection molding industry. Through innovation and collaboration, we have demonstrated that smart-manufacturing techniques like in-mold annealing can provide a competitive edge by enhancing efficiency, reducing costs, and ensuring product quality. This project stands as a testament to our expertise in advanced manufacturing processes and our dedication to driving forward-looking solutions in the field.

VII. ACKNOWLEDGMENT

I would like to express my sincere gratitude to all those who contributed to the successful completion of this project. First and foremost, I would like to thank the engineering, quality, and research and development departments at our customer's company. Their input and collaborative efforts were invaluable, especially in the validation phase, where their rigorous testing and feedback played a crucial role in fine-tuning our process. Their partnership and technical support helped ensure that the in-mold annealing method met all specified performance and durability requirements, reinforcing the importance of close customer collaboration in driving process innovation.

A special thanks goes to the material experts from our Delrin supplier, who provided extensive technical guidance on the material's properties and requirements. Their expertise in acetal resins, particularly in terms of crystallinity and thermal stability, helped us build a solid foundation for this study. Their willingness to share insights and recommendations for the ideal thermal treatment parameters was instrumental in guiding our Design of Experiments and ultimately achieving the desired in-mold annealing results. I deeply appreciate their openness to collaborate and their dedication to supporting our project goals.

I am also grateful to our internal engineering team, who worked tirelessly to design, implement, and optimize the process. Their technical proficiency and commitment to quality were key to overcoming the many challenges we encountered, from setting up the external hot-oil circulation unit to fine-tuning the mold temperature and injection parameters. Each member of the team demonstrated exceptional problem-solving abilities and a commitment to excellence, making this project a true team effort. Their willingness to experiment, adapt, and iterate until we achieved the desired outcomes reflects the culture of innovation within our organization.

Furthermore, I would like to thank our operations team, whose attention to detail and dedication during the transition phase allowed us to implement this process seamlessly into high-volume production. Their efforts to streamline part handling and manage the shift from secondary annealing to in-mold annealing were crucial to our operational success. By ensuring that each new part met quality standards from the outset, they provided a strong backbone to the project, making the transition smooth and efficient.

Lastly, I would like to acknowledge the support of our management team, who not only approved the initial investments required for the external hot-oil unit but also provided the strategic guidance needed to scale this process for future production lines. Their vision and commitment to process improvement empowered us to pursue this innovative solution and reinforce our organization's position as a leader in advanced manufacturing techniques within the plastic injection molding industry.

To everyone involved, your contributions have been invaluable to the success of this project. This achievement would not have been possible without the expertise, dedication, and collaborative spirit of each team member and partner. Thank you for your support and commitment to excellence.

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